Cryocooler Electromagnetic Compatibility

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ABSTRACT

The Jet Propulsion Laboratory, under joint Ballistic Missile and Defense Organization (BMDO)/Air Force and NASA/Eos Atmospheric Infrared Sounder (AIRS) sponsorship, is conducting extensive space cryocooler characterization to provide a reliable and accurate data base on cryocooler performance for use by the space community. As the number of cryocoolers taken through the characterization program increases, it is possible to synthesize the test results to allow performance trends and similarities and differences among the coolers to be observed.

One of the important characteristics of the space cryocooler is the cryocooler's electromagnetic compatibility with the cooled imaging detector, payload instruments, and host spacecraft. Quantification of the cryocooler radiated magnetic and electric field emissions and the conducted power line emissions back onto the spacecraft power bus is extremely important. Data on these attributes is required to determine the degree of shielding or filtering required to insure that the cryocooler electromagnetic signature does not cause malfunction or performance degradation to anything within the spacecraft.

This paper presents typical EMI test results drawn from measurements made on a variety of representative space cryocoolers. The data are presented in comparison with various MIL-STD-461C requirements as a measure of the suitability of the coolers for application aboard sensitive spacecraft.

INTRODUCTION

Mechanical cryocoolers have long been considered an enabling technology for multi-year space missions requiring continuous cryogenic cooling of γ-ray spectrometers and infrared and submillimeter imaging instruments. However, not only must the cooler provide the necessary refrigeration at cryogenic temperatures, it must also be compatible with the sensitive electronic measurements associated with these instruments. EMI and microphonic noise generated by cryocoolers have been an important concern of the cooler user community. While space instrument vibrational susceptibility has been the subject of considerable recent study, the detector and cooler's level of electromagnetic compatibility has received much less emphasis.

Cryocoolers 8, Plenum Publishers, New York, 1995, pp.209-220.

As part of the JPL cryocooler characterization program,[1-4] the electromagnetic signatures of a variety of Stirling cryocoolers have been measured to provide an indication of the level of electromagnetic compatibility of the coolers with the host spacecraft and its payload instruments. All but one of the coolers delivered to JPL for characterization was delivered with laboratory linear power supplies; this limits meaningful EMI measurements to the radiated magnetic and electric field emissions from these coolers. The coolers in this category include the BAe 80 K, BAe 55 K and BAe 50 to 80 K coolers, the Hughes 65 K SSC cooler, the STC 80 K cooler, and the Sunpower Corp. 140 K cooler. The one cooler with flight electronics was the Lockheed- Lucas SCRS cryocooler, which was delivered to JPL for space qualification testing. The Lockheed-Lucas SCRS flight cryocooler and electronics provided the first opportunity to obtain EMI/EMC data, including the conducted power line emissions and the conducted power line susceptibility, on a long-life space cryocooler with flight electronics.

CRYOCOOLER ELECTROMAGNETIC STRUCTURE

The flexure-bearing Stirling cryocooler is a mechanically resonant system that operates much like a loudspeaker. The spring flexure-suspended piston assemblies of both the compressor and displacer are driven via a moving coil in a permanent magnetic field (Fig. 1). Mechanical motion is generated by applying an alternating current through the coils at the drive frequency, typically around 30 to 60 Hz. This frequency is chosen to optimize the thermodynamic performance of the cryocooler, and the compressor is then tuned to be near mechanical resonance at this frequency to maximize the drive motor efficiency. In contrast to the compressor, the displacer is primarily driven by the pneumatic pressure wave from the compressor, with the linear motor used to control the stroke amplitude and phase angle relative to the compressor stroke. Electromagnetic position sensors (generally having excitation frequencies in the kHz range) are used to monitor the position of the linear drive assemblies.

Most space cryocoolers are designed to be driven from the spacecraft 28-Vdc power bus via an electronic invertor that converts the direct current into the alternating current required by the drive motors. The sinusoidal current drawn by the linear motors at their 30- to 60-Hz drive

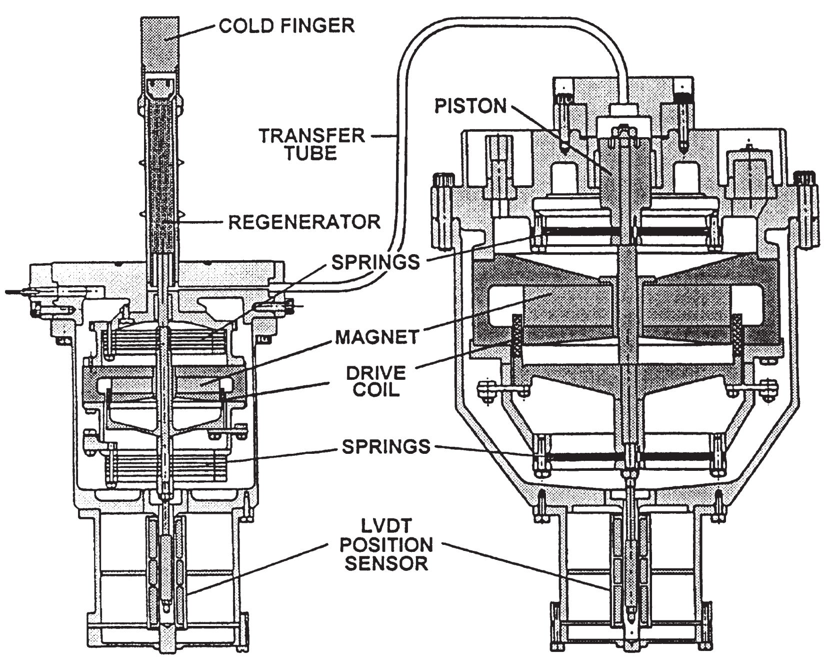

Figure 1. Cross-section of an Oxford-style Stirling-cycle cooler displaying linear drive motors.

frequency results in a large input ripple current at twice the drive frequency; this corresponds to full wave rectification of the drive current. The magnitude of the ripple current is inversely related to the operating DC voltage, and proportional to the operating power. It is difficult to significantly filter this primary ripple current because of its large magnitude and low frequency.

Most cooler drive electronics for space application utilize pulse-width-modulated power converters (PWMs) to synthesize the sinusoidal waveform with maximum efficiency and low harmonic distortion. However, a drawback of the PWMs is the EMI associated with their switching rates in the tens of kHz. This EMI tends to adversely affect adjacent sensitive electronics unless properly filtered and shielded.

The cryocooler and its electronics must not only produce low levels of EMI to be compatible with its surroundings, but must also withstand similar levels of EMI from external sources such as other coolers. This subject of EMI susceptibility is particularly important because many spacecraft are specifying a separate “dirty” power bus to operate the coolers; this leaves the “clean” bus for the sensitive spacecraft science instruments. In addition to voltage and current ripple on the power bus, transient instrument power-ups can produce voltage spikes or draw down the voltage available to the operating cooler over short periods of time. The cooler and electronics must be able to maintain normal operation without malfunctioning under allowable levels of input ripple and voltage transients.

ELECTROMAGNETIC COMPATIBILITY TEST FACILITY

Cryocooler EMI testing at JPL is conducted in the JPL EMC Test Laboratory, which is used for testing all JPL electronics and instruments for space missions. EMI/EMC measurements are performed in a steel RF-shielded room with the facility electronics and cooler ground support electronics (GSE) located in an adjacent room. The cryocoolers (and flight electronics, if available) are placed on top of a copper-laminated table which serves as a ground plane. Cabling from the GSE to the cryocooler/flight electronics is made via a bulkhead plate between the rooms. Any unshielded cabling is sheathed in aluminum foil and grounded to the copper laminated table top to minimize any contributing radiation. Coolers are operated at nominal compressor/displacer stroke for radiated magnetic field emission measurements. EMI data are obtained both with and without the cooler operating to measure cooler-contributed EMI relative to ambient background levels.

ELECTROMAGNETIC COMPATIBILITY MEASUREMENTS

DC Magnetic Field

Most compressors and displacers use permanent magnets with iron pole pieces to provide the magnetic circuit for the drive motors. The resultant DC magnetic dipole fields falls off proportional to $1/R^3$ with increasing distance away from the cooler body; for back-to-back units, designed for vibration control, the resulting magnetic quadrupole field has a corresponding $1/R^4$ dependence with distance. The DC magnetic field profiles are typically measured along the length of the cooler at a particular radial distance from the cooler centerline, and as a function of radial distance away from the compressor or displacer centerline. Measurements are made using Hall generators that are zeroed with the Earth’s magnetic field so that the Earth’s field contribution is not included in the measurements Typical radial and tangential DC magnetic field components measured at a distance of 25 cm from the axis of a back-to-back compressor and displacer assembly of the Lockheed-Lucas SCRS cooler are shown in Fig. 2. Figure 3 shows the magnetic dipole field $1/R^3$ dependence with distance from the end of the SCRS cooler.

Radiated AC Magnetic Field Emissions

Two sets of AC magnetic field measurements are typically made: 1) at a 7-cm distance, corresponding to the MIL-STD-461C REOI test specification[5], and 2) at a 1-m distance, corre-

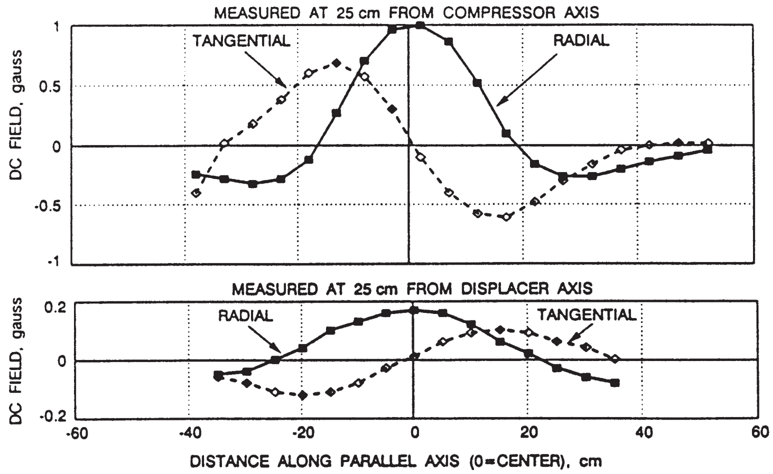

Figure 2. DC magnetic field components at a distance of 25 cm from the axis of the Lockheed-Lucas SCRS back-to-back cooler.

sponding to a MIL-STD-461C RE04 test method. The measurements are made using a standardized 37-turn loop antenna. The 7-cm measurements are made along the spindle axis, 7 cm from the casing of the compressor and displacer units. The cryocooler compressor and displacer spindle axes are generally aligned parallel so measurements of one unit have a small, but discernible radiation component caused by the other unit, e.g. a compressor measurement typically includes an approximate 3-5 dBpT signal from the operating displacer, whereas the displacer measurement may have as much as a 20 dBpT contribution from the compressor.

Compressor radiated magnetic field emissions. The 7-cm measurements of the radiated magnetic field emission levels for several cryocooler compressors are shown in Fig. 4. The data are plotted in decibels above 1 pT; the breaks in the measured data are due to changes in the amplifier gain and spectrum analyzer bandwidth settings. Note that for all coolers the radiated magnetic field emission levels for the fundamental drive frequency are typically in the range of 140 to 160 dBpT (0.1 to 1.0 gauss) at 7 cm, and that the levels at the first three or four harmonics are at or above the current MIL-STD-461C specification. After the first three or four harmonics, the levels

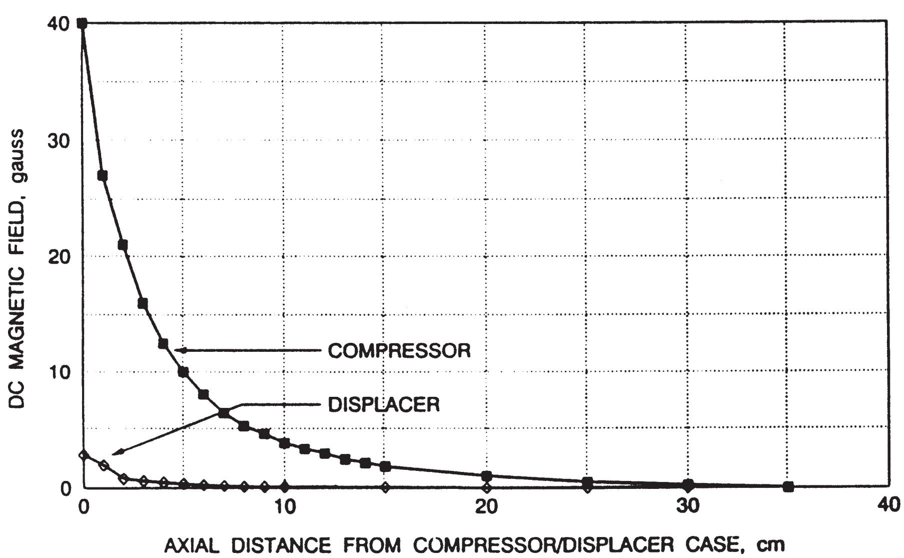

Figure 3. DC magnetic field profile as a function of distance along axes of Lockheed-Lucas SCRS compressor and displacer.

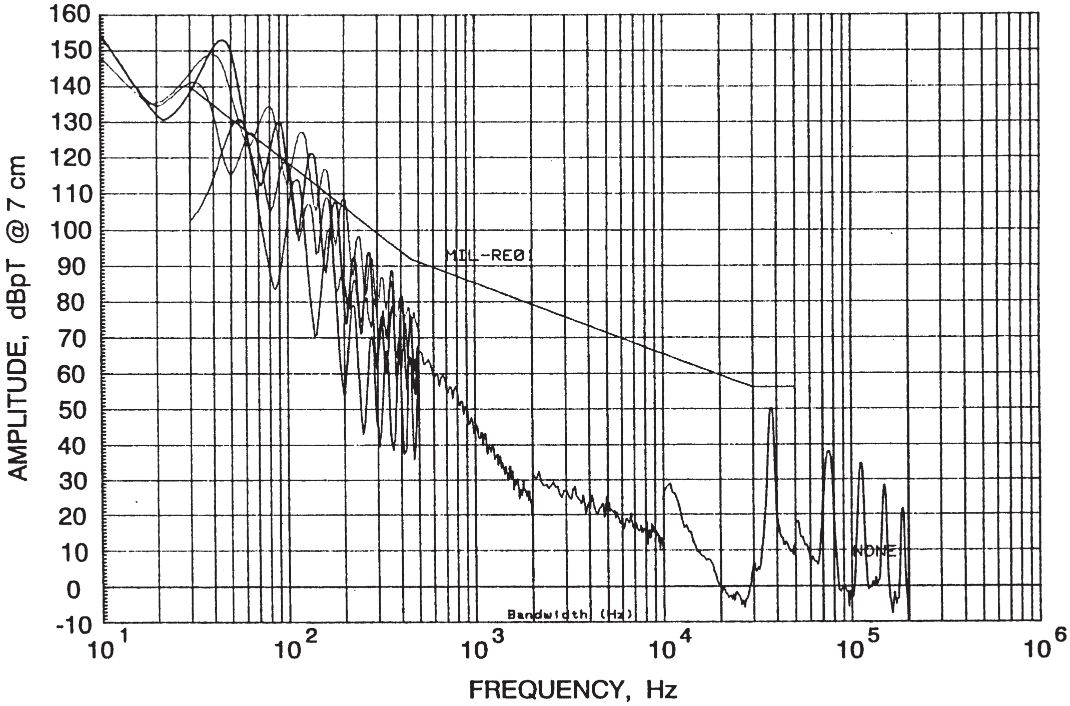

Figure 4. Radiated magnetic field emissions as measured at 7 cm from the compressor of several cryocoolers.

rapidly drop and reach background ambient levels above 1 kHz. The radiated magnetic emissions observed above 10 kHz are the emissions at the 37.5-kHz harmonics of the PWM driving the Lockheed-Lucas SCRS compressor.

As an example, Fig. 5 presents the radiated AC magnetic field emissions of the Lockheed-Lucas SCRS cooler at the 1-meter distance. Again, the radiated magnetic field prominently displays the first few harmonics of the drive frequency.

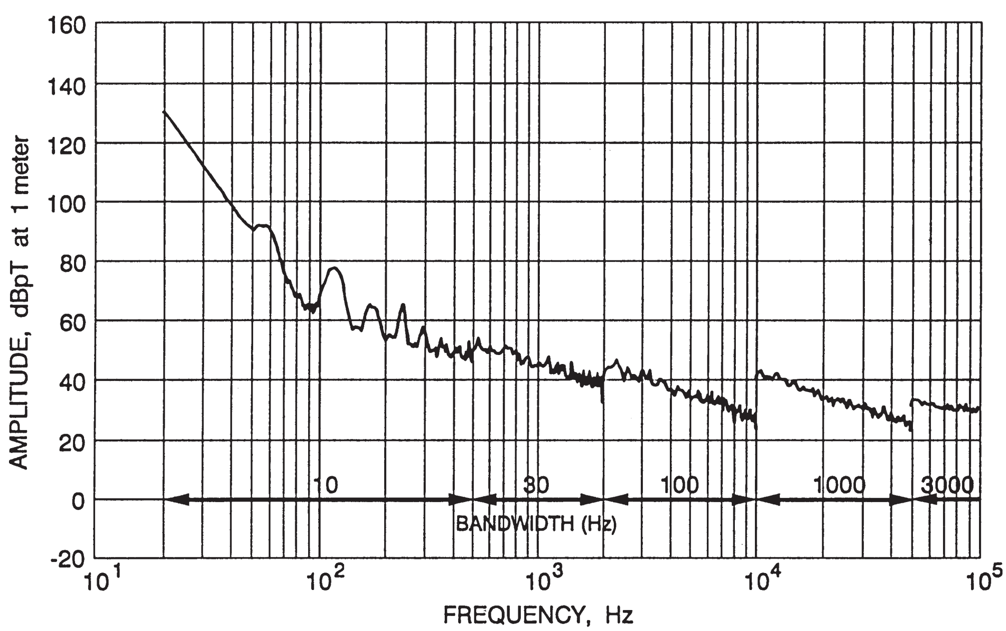

Figure 5. Radiated magnetic field emissions as measured at a 1-m distance from the Lockheed- Lucas SCRS compressor assembly.

Displacer radiated magnetic field emissions. The small drive motor on a typical displacer results in lower radiated magnetic field emissions than are seen from a typical compressor. Radiated magnetic field emission levels at 7 cm for the first few harmonics of the displacers tested at JPL are in the range of 120 to 130 dBpT. Example spectra for several representative displacers are shown in Fig. 6.

AC Magnetic Field Compatibility Tests

A germanium γ-ray spectrometer was integrated onto the displacer coldfinger of a Lockheed-Lucas 1710C cryocooler to test the applicability of coolers to high resolution spectroscopy in multi-year space-based science missions. The detector is particularly susceptible to capacitance changes between the gate lead to the cryogenically-cooled FET preamp and the high voltage supply, and minute motions of the gate lead can cause signal degradation. The detector's energy resolution was monitored using two calibrated keV-level γ-ray sources. The energy widths of the signals were compared for conditions with the cooler both operating and non-operating to determine if the cooler-generated EMI and microphonic noise would cause degradation of the detector's sensitivity. No signs of spectral broadening were observed in the detector signal, indicating the spectrometer was not affected by either the displacer vibration or the EMI.

Radiated Electric Field Emissions

Narrowband and broadband radiated electric field emissions are measured at a distance of 1 meter from the geometric center of the cryocooler. The measured emission levels are compared to MIL-STD-461C RE02 narrowband and broadband electric field emission specifications. Several antennas are used to measure the emissions up to a frequency of 10 GHz. Discontinuities in the data are changes in the antennas, amplifiers, and bandwidths used to cover the different frequency bands.

Electric field emission measurements for coolers driven with linear laboratory power supplies show no significant emissions that exceed MIL-STD-461C RE02 specifications. Spectral peaks that exceed MIL-STD-461C RE02 specifications are invariably traced to the GSE.

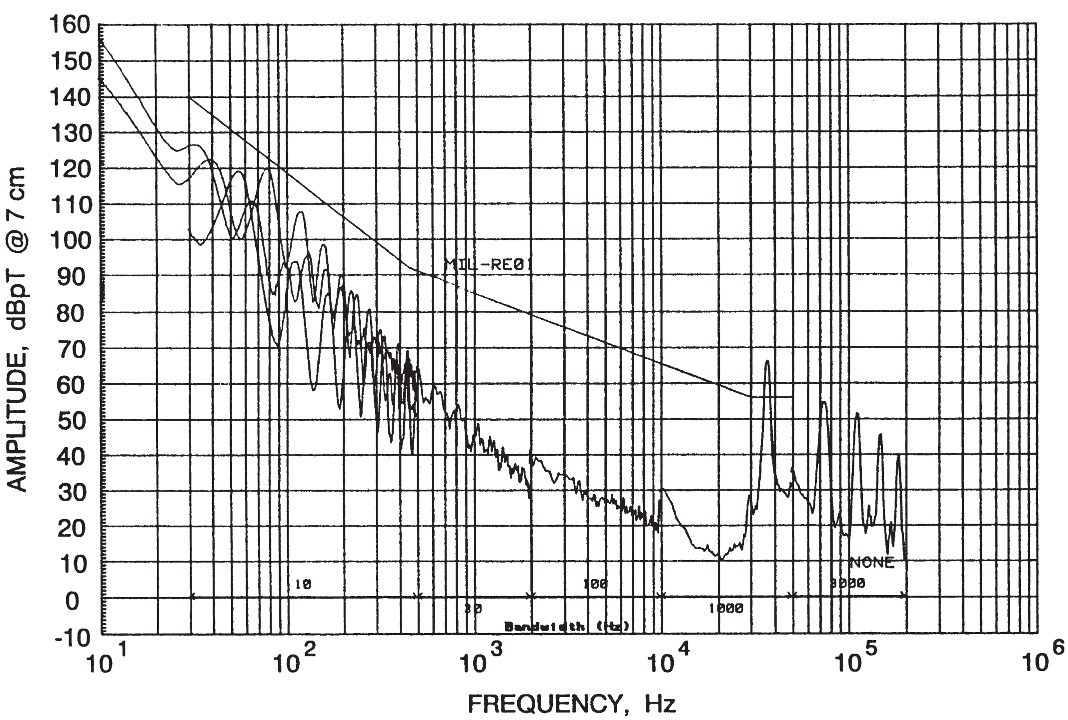

Figure 6. Radiated magnetic field emissions as measured at 7 cm from the displacers of several cryocoolers.

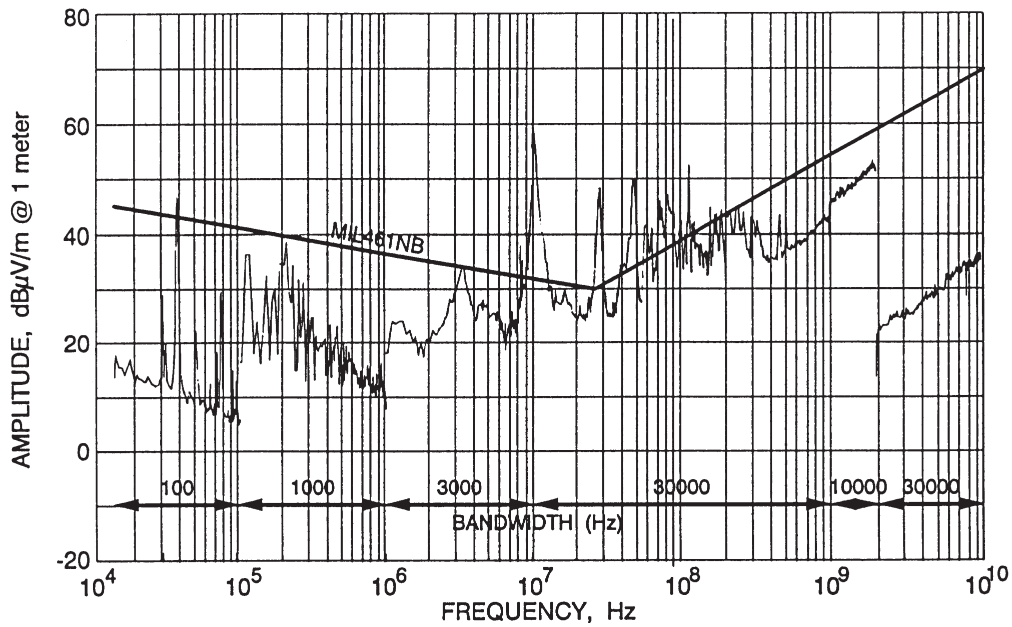

Figure 7. Narrowband electric field emissions as measured at a 1-m distance from the Lockheed-Lucas SCRS cryocooler.

Example electric field emissions for the Lockheed-Lucas SCRS flight cooler and flight electronics are shown in Figs. 7 and 8. Measurements were conducted under different operating conditions to distinguish between actual cryocooler/flight electronics emissions and emissions due to the non-flight ground support equipment (GSE). It was determined that most of the broad peaks rising above the MIL-STD specification were due to the GSE. The only electric field emissions of any significance radiating from the cooler were at the 37.5-kHz PWM switching frequency and its harmonics.

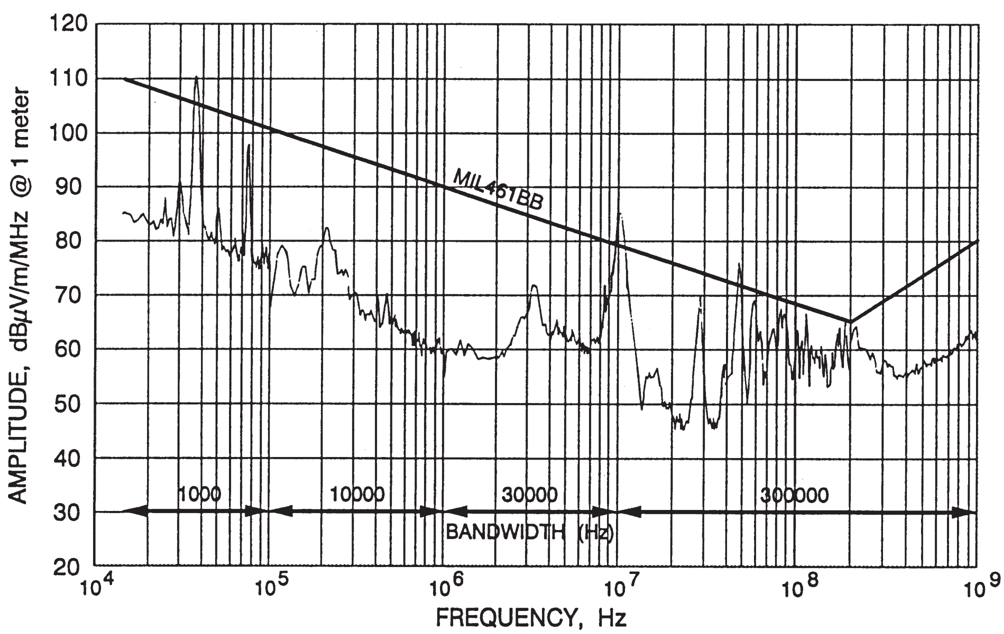

Figure 8. Broadband electric field emissions as measured at a 1-m distance from the Lockheed-Lucas SCRS cryocooler.

Conducted Emissions

Because of the lack of flight electronics from other manufacturers, conducted emissions measurements have only been made on the Lockheed-Lucas SCRS flight cooler. The SCRS cryocooler +28 Volt power lines were tested for ripple current emissions in both the narrowband and broadband frequency spectrums. Measurements were conducted on both the high-side (positive) and return (negative) lines using a current probe. A line impedance simulation network was inserted in the 28 Volt line to closely simulate the spacecraft bus power impedance. The test configuration for the power bus measurements is shown in Fig. 9.

Figures 10 and 11 are the narrowband and broadband conducted emissions profiles on the 28 Volt active (positive) lead. The specification line is that of MIL-STD-461 CE01/03. The harmonics of the 56-Hz drive frequency are clearly observable. So too are the harmonics of the compressor pulse-width-modulated power converters which are switching at 37.5 kHz, The return (negative) lead current emission profiles have identical emission levels for the cooler drive harmonics, but have emission levels 20 dB higher for the harmonics of the 37.5-kHz PWM switching frequency. Except for a few over-spec peaks at the 56-Hz second harmonic, the power line ripple in the active power lead is within specification at most frequencies. In the return (negative) lead, emissions are most noticeably above the specification at harmonics of 37.5 kHz. Although the active and return broadband emissions both show out-of-specification conditions at 37.5 kHz and related harmonics, the emissions are purely narrowband, and thus should not be considered as broadband emissions.

Voltage and Current Ripple Test Results (Time Domain). The time domain voltage and current ripple were also measured on the 28 volt power line with the Lockheed-Lucas SCRS cooler. At the input to the cryocooler flight electronics, the ripple voltage reflected back onto the 28 volt power line measured 1.32 volts peak-to-peak (Fig. 12). The current ripple reflected back onto the 28 volt power line measured approximately 7 amps peak-to-peak and is shown in Fig. 13. The cooler was operating with a refrigeration load at 58 K and drawing an RMS current of 6.7 amps. These high voltage/current ripple levels reflected back onto the spacecraft bus are an incentive for providing a separate “dirty” bus for the cryocooler.

Power-On Inrush Current/Transient Voltage (Time Domain). The Lockheed-Lucas SCRS flight electronics was tested for inrush current as well as transient voltage when the 28-V power is switched from OFF to ON using the switch inserted in series with the active lead to the cooler flight electronics (Fig. 9). Figure 14 shows the inrush current profile and the voltage transient created when the flight electronics was turned from OFF to ON. A peak inrush current of 6.4 amps was measured, with the transient lasting approximately 40 msec. A peak voltage transient of 0.7 volts was measured. The spikes occurring before the initial turn-on transient are caused by the switch bounce and should not be considered as being part of the turn-on voltage transient. It should be noted here that after turn-on, the compressor and then the displacer were enabled, but no reflected voltage or current was observed.

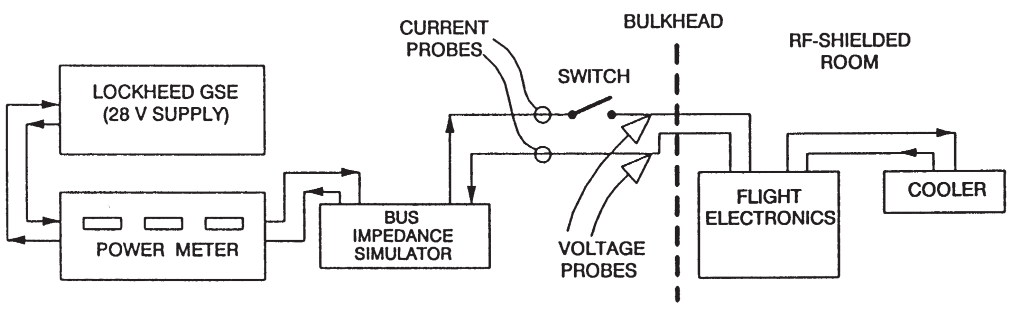

Figure 9. Test configuration for Lockheed SCRS cryocooler EMI/EMC measurements.

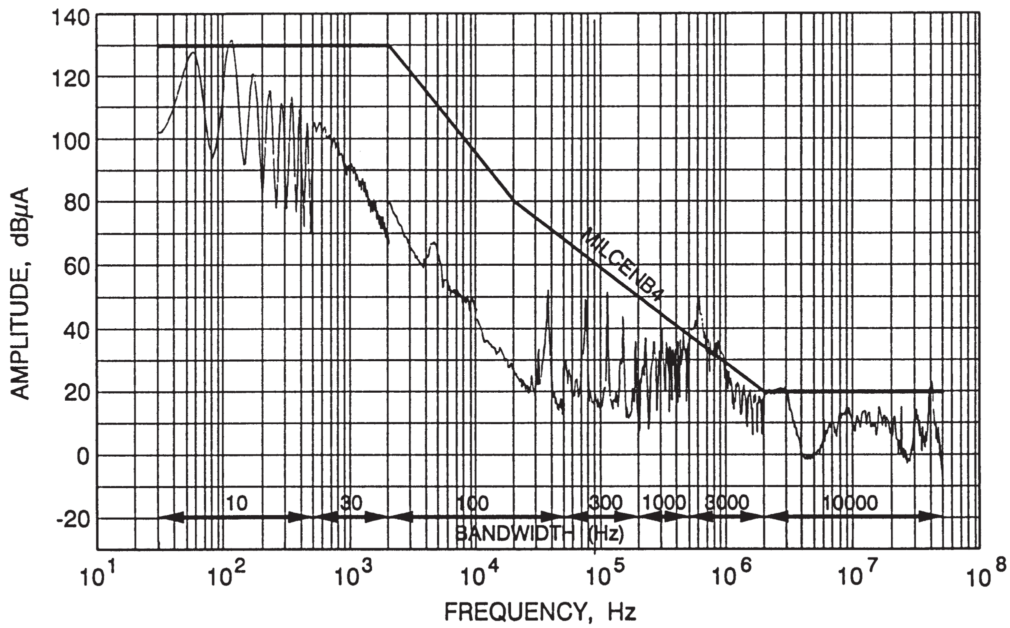

Figure 10. Narrowband conducted emissions profile on the positive 28 volt line of the Lockheed-Lucas SCRS cryocooler.

Conducted Susceptibility

Two susceptibility tests were conducted on the Lockheed-Lucas SCRS cryocooler's flight electronics 28 volt power input. Negative and positive voltage transients of 10-μsec duration were injected on the active lead via a transformer coupled method. A 300-Hz negative-going transient of -28 volts$_{0\text{-}p}$ was injected on the positive power lead for approximately 5 minutes. The 300-Hz transient was then reversed in polarity, but its amplitude set to +14 volts$_{0\text{-}p}$ run for another 5 minutes. No anomalies in cryocooler operation or performance were noted.

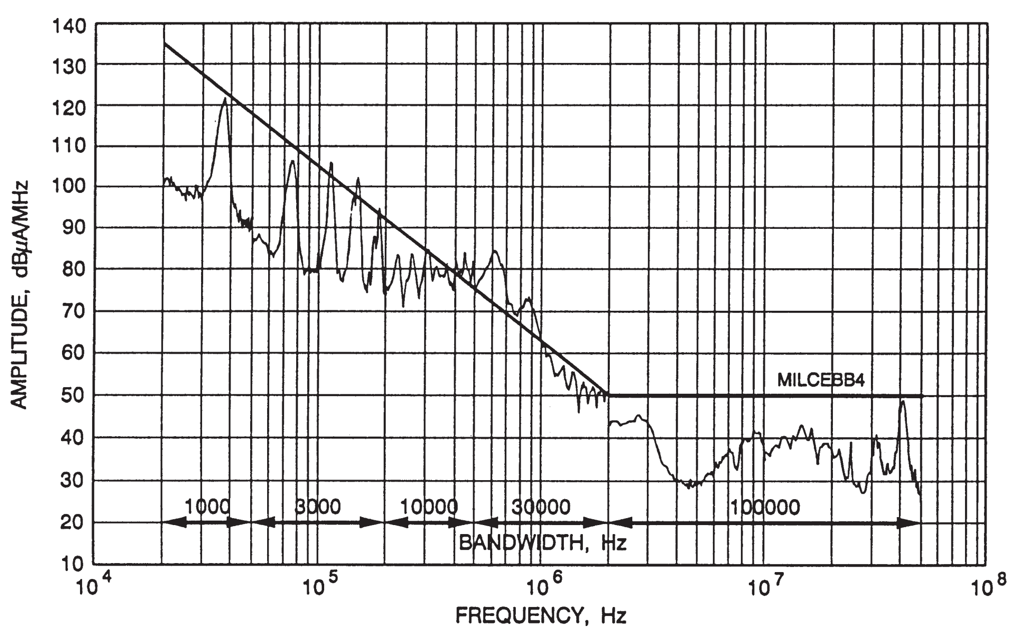

Figure 11. Broadband conducted emissions profile on the positive 28 volt line of the Lockheed-Lucas SCRS cryocooler.

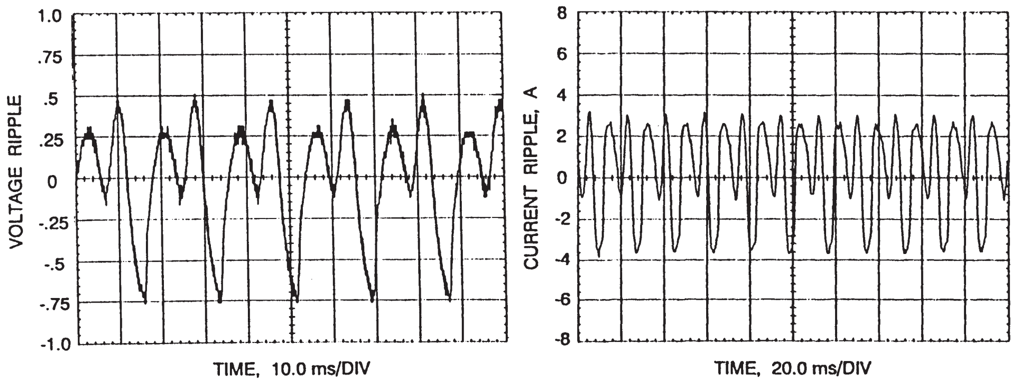

Figure 12. Voltage and current ripple reflected back onto the 28 volt power line from the Lockheed-Lucas SCRS cryocooler. (RMS current = 6.7 A).

A 1.6-$V_{0\text{-}p}$ sinusoidal voltage ripple varying in frequency from DC to 100 kHz was injected on the same power lead, again using a transformer coupled method. The sinusoidal noise was injected inductively using a current probe clamped over the positive lead, immediately before the cooler flight electronics. Again, no anomalies were observed in the cryocooler operation or performance.

DISCUSSION

Spacecraft instrument interface requirements place limits on the magnetic fields emitted from science instruments to insure that magnetic fields do not interfere with the operation of other spacecraft instruments, nor produce significant magnetic torques on the overall spacecraft. The 100-μT (1 gauss) DC magnetic field strength as measured at 25 cm from the Lockheed-Lucas flight cooler is on the same order of magnitude as the earth's magnetic field strength, and is almost an order of magnitude lower than the magnetic field strength of the magnetic torquers used

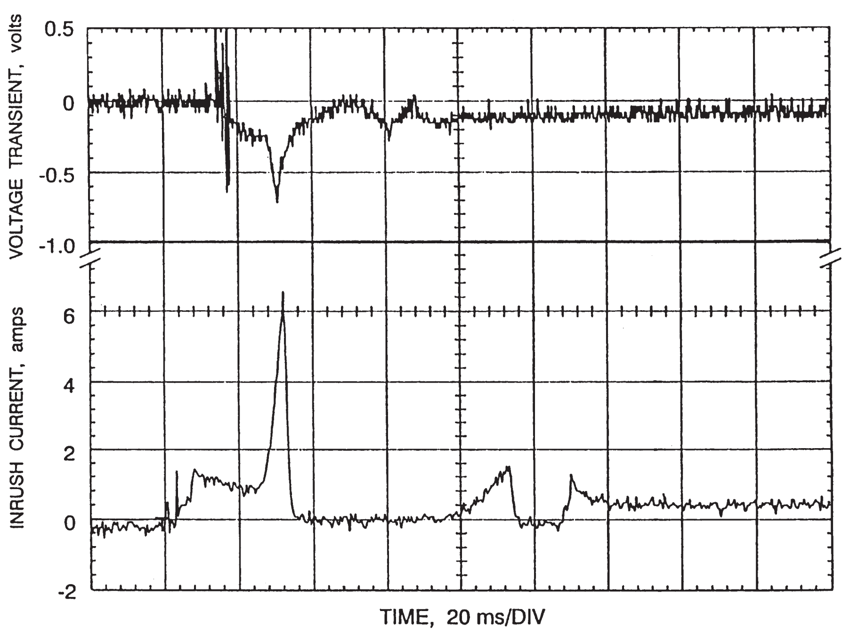

Figure 13. Voltage transient and inrush current profile created when the Lockheed-Lucas SCRS flight electronics was switched from OFF to ON.

on many spacecraft. However, this level is potentially high enough to cause concern with sensitive spacecraft instruments.

The results of the radiated AC magnetic field measurements indicate that some level of shielding with mu-metal (perhaps 0.5 to 1.5 mm thick) will be required to lower the AC magnetic field levels to below the MIL-STD-461C specification. The thickness and geometry of the shielding will depend on the number of coolers required on the spacecraft, and where and how they are configured. A modest mass penalty may be imposed on the instrument by the requirement that the shield be made thick enough to facilitate the necessary shielding and have a fundamental vibration frequency high enough not to couple into the cooler vibration harmonics.

The radiated AC electric field emissions from the Lockheed-Lucas flight cooler and electronics that rose above the MIL-STD-461C specification were found to be due to the PWMs in the compressor drive circuit of the flight electronics. If required, electrostatic shielding can be placed around instrument electronics to reduce the level of capacitive coupling of the electric field to the electronics.

These initial measurements of the cooler's radiated magnetic and electric field emissions provide the needed data to make estimates of the levels of induced voltages that may couple into the detector signal. These estimates can be made using near-field, common-mode coupling equations:[6]

$$V_{i,E} = \sqrt{2}\, LE \sin(\pi h / \sqrt{2}\lambda), \text{ volts}$$

$$V_{i,B} = \sqrt{2}\, LcB \sin(\pi h / \sqrt{2}\lambda), \text{ volts}$$

where $V_{i,E}$ is the induced voltage due to the electric field intensity E, $V_{i,B}$ is the induced voltage due to the magnetic flux density B, λ=c/f is the wavelength corresponding to the radiated emission frequency f, h is the separation distance between a pair of sensor leads of length L. To get an appreciation for the level of coupling of the radiated emissions to a pair of sensor leads consider a sensor located 20 cm from the radiation source having a pair of untwisted leads 2 cm in length and separated by 2 mm. From the data in Figs 4 and 7, consider the 152-dBpT magnetic spectral peak at 45 Hz, and the 47-dBμV/m electric field spectral level at 38 kHz. Adjusting these values for the 20-cm distance at the sensor, the resultant induced voltages are on the order of 20 nV and 0.002 nV for the magnetic and electric fields, respectively. These order of magnitude values for the induced voltages are quite small and in general negligible. However for sensitive detectors such as bolometers and SIS receivers where the pre-amplified signal levels are in the nano-volt range, these induced voltages are quite problematic and require attention. Integrated detector/cooler tests will have to be conducted to determine final shielding requirements and insure electromagnetic compatibility.

The results of the conducted emissions measurements with the flight electronics show the large level of voltage and current ripple that the cooler reflects back onto the spacecraft power bus. The inclusion of a "dirty" bus for cooler operation on the spacecraft reduces the risk of degrading flight instrumentation operation and measurements. The robustness of the Lockheed- Lucas SCRS flight cooler and drive electronics to power-line conducted emissions and powerline voltage transients and ripple has been demonstrated. Powerline transients due to the cooler operation should be of minimum concern because normal cooler operation uses soft start-ups whereby the cooler is powered up slowly until the piston stroke is increased to its operating amplitude. In addition, the drive power required to operate the cooler increases slowly from about 50% of full power to full power as the coldtip cools from ambient temperature to 55 K.[7]

SUMMARY

Early EMC testing provides a sensitivity check on the generated EMI level and indicates whether mu-metal shielding or electrostatic shielding is required and sufficient to insure EMI levels are compatible with spacecraft instruments. Even though the low frequency radiated magnetic field emissions are above the MIL-STD-461C specifications, the estimated EMI-induced voltages are quite small and may be tolerable in all but the most sensitive applications. The successful compatibility tests with the integrated γ-ray spectrometer/cryocooler support this conclusion.

The Lockheed-Lucas SCRS flight cooler provided the first opportunity to obtain EMI/EMC information regarding flight electronics. Measurements of the magnetic, electric and conducted emissions showed some drive frequency harmonics and PWM frequency harmonics to be above the MIL-STD-461C specifications. The prevalence of the high emissions levels from the PWMs in all radiated and conducted emissions measurements suggest that additional line filtering or circuit board shielding is required to reduce these levels. The extent that these high levels will interfere or degrade the signal of the intended detector will not be known until integrated detector/cryocooler tests are performed. It is not until integration into the spacecraft that system level EMI testing will reveal the final amount of mu-metal shielding or filtering that will be required to protect the host spacecraft or the adjacent spacecraft instruments.

ACKNOWLEDGMENT

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Particular credit is due P. Narvaez of JPL, who conducted the EMC measurements, and to E. Jetter for preparation of the artwork presented here. The financial support of JPL's AIRS instrument and the Air Force Phillips Laboratory and the BMDO is graciously acknowledged.

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